

750 GeV diphoton excess confronted with a top-pion in the TTM model

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Abstract

The latest LHC data suggest an intriguing excess at $m_{\gamma\gamma} = 750$ GeV which apparently requires an explanation from the beyond standard model physics. In this note we explore the possibility for this signal to arise from a top-pion in the Top Triangle Moose model which can be viewed as a dimensional-deconstruction version of the top-color assisted technicolor model. We demonstrate that the observed excess can be accommodated by and has important implications for this interesting model.

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I. INTRODUCTION

Recently, the first data obtained at the LHC Run 2 with a center-of-mass energy $\sqrt{s} = 13$ TeV have been released. Interestingly, both the ATLAS and CMS collaborations have observed an excess in the diphoton invariant mass distribution around 750 GeV, with the 3.9σ [1] and 2.6σ [2] significance respectively. Interpreted in terms of a resonance induced by one (pseudo)scalar S of the mass 750 GeV, this signal indicates that the production cross section times the $\gamma\gamma$ branching ratio of S has a value of [1, 2]

$$\sigma(pp \rightarrow S)\text{Br}(S \rightarrow \gamma\gamma) = \begin{cases} (10 \pm 3) \text{ fb} & (\sqrt{s} = 13\text{TeV ATLAS}) , \\ (6 \pm 3) \text{ fb} & (\sqrt{s} = 13\text{TeV CMS}) . \end{cases} \quad (1)$$

In addition, the ATLAS excess features a width of about 45 GeV at the face value while the CMS excess width is narrow and inconclusive [3]. We will therefore take seriously the suggestive peak position and signal cross section, but just consider the width value as a reference in the following analysis.

If established, this excess would very likely lead us to some new physics beyond the standard model (SM). In this connection various interesting possibilities have been proposed to explain the signal [4–66]. One solution of particular interest is to consider S as a composite particle due to the confinement of a new strong dynamics [67–81]. This idea can be traced back to the technicolor (TC) theory which serves as an alternative for the electroweak symmetry breaking [82]. In TC models, there are generally many massless techniquarks introduced which will result in a large chiral symmetry. When the chiral symmetry is spontaneously broken by the techniquark condensation, some Goldstone bosons corresponding to the broken symmetries (except those to the broken electroweak symmetries) will arise which are unique composite pseudoscalar candidates. An interesting TC model is the one assisted by an additional strong interaction — top-color, as the name suggests, which only acts on the third generation quarks [83]. This model can naturally accounts for the largeness of m_t via the top-quark condensation, while the electroweak symmetry breaking still mainly comes from the conventional TC sector. Noteworthy, there will be three additional Goldstone bosons called top-pions that correspond to the broken chiral symmetries involving t and b .

In this short note we will investigate the possibility for S to be a neutral top-pion from the Top Triangle Moose (TTM) model [84, 86–89] which can be viewed as a dimensional-deconstruction [95, 96] version of the top-color assisted TC model [90–94]. In the next section, we will first recapitulate the essential features and relevant details of TTM model and then perform numerical analysis to show that the experimental result can be fitted. Our conclusions and some further discussions will be given in the last section.

II. FRAMEWORK AND ANALYSIS

A. The TTM model revisited

The TTM model [84, 85] was originally proposed for reducing the tension between obtaining a realistic top-quark mass and fulfilling the electroweak precision measurements,

which exists in the three-site Higgsless model [97]. This is achieved by separating the bulk of electroweak symmetry breaking from that of top-quark mass generation, resembling the top-color assisted TC model [83]. In the TTM model, one invokes the gauge interactions $SU(2)_0 \times SU(2)_1 \times U(1)_2$ (with the respective couplings g , \tilde{g} and g') under which the fermion fields furnish the following representations:

$$Q_{L0} \sim (2, 1, \frac{1}{6}), \quad Q_{L1} \& Q_{R1} \sim (1, 2, \frac{1}{6}), \quad u_{R2} \sim (1, 1, \frac{2}{3}), \quad d_{R2} \sim (1, 1, -\frac{1}{3}). \quad (2)$$

Note that we introduce a vector-like partner for every SM fermion, which is allowed to assume a mass term $M_D \overline{Q_{L1}} Q_{R1}$ in the first place.

In order to break $SU(2)_0 \times SU(2)_1 \times U(1)_2$ down to the electromagnetism interaction as well as generate masses for the massless quarks, two bi-fundamental fields Σ_{01} and Σ_{12} together with a top-Higgs field Φ are introduced. While Φ carries a quantum number of $(2, 1, -1/2)$, Σ_{01} and Σ_{12} are non-linear sigma model fields with the related covariant derivatives being

$$\begin{aligned} D_\mu \Sigma_{01} &= \partial_\mu \Sigma_{01} + ig W_{0\mu} \Sigma_{01} - i\tilde{g} \Sigma_{01} W_{1\mu}, \\ D_\mu \Sigma_{12} &= \partial_\mu \Sigma_{12} + i\tilde{g} W_{1\mu} \Sigma_{12} - ig' \Sigma_{12} \tau^3 B_\mu. \end{aligned} \quad (3)$$

It is understood that $W_{0\mu} = W_{0\mu}^a \tau^a$ and $W_{1\mu} = W_{1\mu}^a \tau^a$ with $\tau^a = \sigma^a/2$ (for $a = 1, 2, 3$) being the generators of $SU(2)$. These scalar fields will develop vacuum expectation values (VEVs) and can be expanded around their VEVs as follows

$$\begin{aligned} \Sigma_{01} &\sim \frac{1}{\sqrt{2}} v \cos \omega \mathbf{1}_{2 \times 2} + i\tau^a \pi_0^a, \\ \Sigma_{12} &\sim \frac{1}{\sqrt{2}} v \cos \omega \mathbf{1}_{2 \times 2} + i\tau^a \pi_1^a, \end{aligned} \quad \Phi \sim \begin{pmatrix} \frac{1}{\sqrt{2}} (v \sin \omega + H_t + i\pi_t^0) \\ i\pi_t^- \end{pmatrix}, \quad (4)$$

where ω is used to parameterize the partition of electroweak symmetry breaking (equivalently v) among the different sectors. Six combinations of the above degrees of freedom will be eaten, generating masses for the two sets of weak bosons — W^\pm , Z^0 and W'^\pm , Z'^0 . And there exists a mass relation between W^\pm and W'^\pm as given by

$$\frac{M_W^2}{M_{W'}^2} = \frac{g^2}{4\tilde{g}^2 \cos^2 \omega}. \quad (5)$$

For phenomenological considerations (which demand $M_W \ll M_{W'}$), $x \equiv g/\tilde{g}$ is required to be a small quantity. Hence we are left with four uneaten states, namely H_t (called top-Higgs) and one iso-triplet (called top-pions)

$$\Pi_t^a = -\sin \omega \left(\frac{\pi_0^a + \pi_1^a}{\sqrt{2}} \right) + \cos \omega \pi_t^a. \quad (6)$$

They receive their masses mainly from the following interactions [84, 85]:

$$\lambda \text{Tr} \left(M^\dagger M - \frac{f^2}{2} \right)^2 + \kappa f^2 \text{Tr} \left| M - \frac{f}{\sqrt{2}} \Sigma_{01} \Sigma_{12} \right|^2, \quad (7)$$

with

$$M = \begin{pmatrix} i\pi_t^+ & (f + H_t + i\pi_t^0)/\sqrt{2} \\ (f + H_t - i\pi_t^0)/\sqrt{2} & i\pi_t^- \end{pmatrix}. \quad (8)$$

A straightforward calculation gives us the top-Higgs and top-pion masses as

$$M_H^2 = 2v^2(\kappa + 4\lambda)\sin^2\omega, \quad M_{\Pi_t}^2 = 2v^2\kappa\tan^2\omega. \quad (9)$$

In addition, these interactions give rise to the trilinear coupling among three top-pions

$$g_{\Pi_t^0\Pi_t^+\Pi_t^-}\Pi_t^0\Pi_t^+\Pi_t^- = 2i\kappa v\sin^2\omega\tan^2\omega\Pi_t^0\Pi_t^+\Pi_t^-, \quad (10)$$

which will contribute to the loop process of diphoton emission.

On the other hand, Σ_{01} , Σ_{12} and Φ also contribute to fermion masses by virtue of the Yukawa interactions

$$M_D \left[\epsilon_L \overline{Q}_{L0} \Sigma_{01} Q_{R1} + \overline{Q}_{L1} \Sigma_{12} \begin{pmatrix} \epsilon_{uR} \\ \epsilon_{dR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix} \right] + \lambda_u \overline{Q}_{L0} \Phi u_{R2} + \lambda_d \overline{Q}_{L0} \Phi d_{R2}. \quad (11)$$

Here ϵ_L is a flavor-universal parameter and has to be approximately $x/\sqrt{2}$ in order for the SM fermions to decouple from W' [98], while ϵ_{fR} is flavor dependent. It should be mentioned that ϵ_{tR} is subject to the precision measurement constraint [97]

$$\frac{M_D^2 \epsilon_{tR}^4}{16\pi^2 v^2} < \mathcal{O}(10^{-3}). \quad (12)$$

To mimic the role of top-color, Φ is assumed to couple with the third generation fermions preferentially, implying that only λ_t , λ_b and λ_τ of the λ_f 's are considerable. The mass matrix for t and its vector-like partner T (similarly for b and its vector-like partner B) as well as the resulting mass eigenvalues thus turns out to be

$$M_t = M_D \begin{pmatrix} a & \epsilon_L \\ \epsilon_{tR} & 1 \end{pmatrix} \implies \begin{cases} m_t = \frac{1}{\sqrt{2}} \lambda_t v \sin\omega \left[1 + \frac{a\epsilon_L^2 + a\epsilon_{tR}^2 + 2\epsilon_L\epsilon_{tR}}{2(-a + a^3)} \right], \\ m_T = M_D \left[1 - \frac{\epsilon_L^2 + \epsilon_{tR}^2 + 2a\epsilon_L\epsilon_{tR}}{2(-1 + a^2)} \right], \end{cases} \quad (13)$$

where a stands for $\lambda_t v \sin\omega/(\sqrt{2}M_D)$. For the mass matrices of the first two generation fermions, there will not be a term like the a in Eq. (13). Consequently, the mass eigenvalues for these SM fermions and their vector-like partners are about $M_D\epsilon_L\epsilon_{fR}$ and M_D , respectively.

B. Numerical results

Before performing the numerical calculations, let us present some relevant details and useful formulas concerning the decay of Π_t^0 . By inserting Eqs. (4, 6) into Eq. (11), one may easily derive the couplings between Π_t^0 and the SM fermions [84, 85]

$$\frac{i\Pi_t^0}{v} (m_t \cot\omega \overline{t}_L t_R + m_b \cot\omega \overline{b}_L b_R + m_\tau \cot\omega \overline{\tau}_L \tau_R + m_c \tan\omega \overline{c}_L c_R). \quad (14)$$

The decay widths for these processes can be calculated according to

$$\Gamma(\Pi_t^0 \rightarrow t\bar{t}) = \frac{3m_t^2}{8\pi v^2} \cot^2 \omega \, m_{\Pi_t} \beta_{tt} , \quad \Gamma(\Pi_t^0 \rightarrow c\bar{c}) = \frac{3m_c^2}{8\pi v^2} \tan^2 \omega \, m_{\Pi_t} \beta_{cc} , \quad (15)$$

where $\beta_{\alpha\beta}$ reads as

$$\beta_{\alpha\beta} = \lambda^{1/2} \left(\frac{m_\alpha^2}{m_{\Pi_t}^2}, \frac{m_\beta^2}{m_{\Pi_t}^2} \right) , \quad \text{with} \quad \lambda(\alpha, \beta) = 1 + \alpha^2 + \beta^2 - 2\alpha - 2\beta - 2\alpha\beta . \quad (16)$$

Apparently, the width of $\Pi_t^0 \rightarrow c\bar{c}$ may be comparable to and even exceed that of $\Pi_t^0 \rightarrow t\bar{t}$ when $\tan \omega$ is large enough, while the widths of $\Pi_t^0 \rightarrow b\bar{b}$ and $\Pi_t^0 \rightarrow \tau\bar{\tau}$ are always much smaller than that of $\Pi_t^0 \rightarrow t\bar{t}$. The decays to $t\bar{T}$ and $T\bar{T}$ will also be included, if kinematically allowed, for which the associated couplings are obtained as [84, 85]

$$\begin{aligned} g_{\Pi_t^0 \bar{T}_L T_R} &= \frac{i\lambda_t}{4\sqrt{2}} \left[\frac{2\sqrt{2}x\epsilon_{tR}(a^2 + \cos 2\omega) + (2a^2 \cos \omega + (a^2 - 1) \sin \omega \tan \omega)(x^2 + 2\epsilon_{tR}^2)}{(a^2 - 1)^2} \right] , \\ g_{\Pi_t^0 \bar{t}_L T_R} &= \frac{i\lambda_t}{(a^2 - 1)} \left[\frac{x \sec \omega (-1 + 3a^2 + (1 + a^2) \cos 2\omega)}{8a} + \frac{\epsilon_{tR} \cos \omega}{\sqrt{2}} \right] , \\ g_{\Pi_t^0 \bar{T}_L t_R} &= \frac{i\lambda_t}{(a^2 - 1)} \left[\frac{x \cos \omega}{2} + \frac{\epsilon_{tR} \sec \omega (-1 + 3a^2 + (1 + a^2) \cos 2\omega)}{4\sqrt{2}a} \right] . \end{aligned} \quad (17)$$

Similar to the SM Higgs h , Π_t^0 can also decay to two photons (gluons) through the charged (colored) fermion triangle loops. And the corresponding decay widths are given by

$$\begin{aligned} \Gamma(\Pi_t^0 \rightarrow \gamma\gamma) &= \frac{G_\mu \alpha^2 m_{\Pi_t}^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 F(\tau)_{1/2}^A \alpha_f + \frac{v g_{\Pi_t^0 \Pi_t^+ \Pi_t^-}}{2M_{\Pi_t}^2} F(\tau)_0^A \right|^2 , \\ \Gamma(\Pi_t^0 \rightarrow gg) &= \frac{G_\mu \alpha_s^2 m_{\Pi_t}^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f F(\tau)_{1/2}^A \alpha_f \right|^2 , \end{aligned} \quad (18)$$

by analogy with those for h , with $\alpha_f \equiv g_{\Pi_t^0 \bar{f}f}/g_{h\bar{f}f}$ being the relative coupling strength (e.g., $\alpha_t = \cot \omega$). In the above G_μ stands for the Fermi constant $1.17 \times 10^{-5} \text{ GeV}^{-2}$, whereas the symbols α , α_s , N_c and Q_f are self-explanatory. Furthermore, the loop functions $F(\tau)_{1/2}^A$ and $F(\tau)_0^A$ are given by [99]

$$F(\tau)_{1/2}^A = 2\tau f(\tau) , \quad F(\tau)_0^A = -\left[\frac{1}{\tau} - f(\tau) \right] \tau^2 , \quad (19)$$

with $\tau_f \equiv 4m_f^2/M_{\Pi_t}^2$ and

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{1/\tau} & \text{if } \tau \geq 1 , \\ -\frac{1}{4} [\ln(\eta_+/\eta_-) - i\pi]^2 & \text{if } \tau < 1 , \end{cases} \quad (20)$$

for $\eta_{\pm} = (1 \pm \sqrt{1 - \tau})$. In the summation over fermions, we will include t , b , c , T and τ . In contrast, only Π_t^{\pm} take effect via the scalar loop.

In order to reproduce the observed diphoton excess in terms of the Π_t^0 resonance, one needs to have

$$\sigma(pp \rightarrow \Pi_t^0 \rightarrow \gamma\gamma) = \frac{1}{m_{\Pi_t} \Gamma_s} \left[C_{gg} \Gamma(\Pi_t^0 \rightarrow gg) + \sum_q C_{q\bar{q}} \Gamma(\Pi_t^0 \rightarrow q\bar{q}) \right] \Gamma(\Pi_t^0 \rightarrow \gamma\gamma) \quad (21)$$

$(10 \pm 3)\text{fb}$ for $\sqrt{s} = 13 \text{ TeV}$. Here Γ is the total width of Π_t^0 and approximates to

$$\begin{aligned} \Gamma \simeq & \Gamma(\Pi_t^0 \rightarrow gg) + \Gamma(\Pi_t^0 \rightarrow t\bar{t}) + \Gamma(\Pi_t^0 \rightarrow b\bar{b}) + \Gamma(\Pi_t^0 \rightarrow c\bar{c}) + \Gamma(\Pi_t^0 \rightarrow \tau\bar{\tau}) \\ & + \Gamma(\Pi_t^0 \rightarrow \bar{t}T) + \Gamma(\Pi_t^0 \rightarrow T\bar{T}) , \end{aligned} \quad (22)$$

while C_{gg} and $C_{q\bar{q}}$ are the dimensionless partonic integral functions [3]

$$\begin{aligned} C_{gg} &= \frac{\pi^2}{8} \int_{m_{\Pi_t}^2/s}^1 \frac{dz}{z} g(z) g\left(\frac{M^2}{sz}\right) , \\ C_{q\bar{q}} &= \frac{4\pi^2}{9} \int_{m_{\Pi_t}^2/s}^1 \frac{dz}{z} \left[q(z) \bar{q}\left(\frac{m_{\Pi_t}^2}{sz}\right) + \bar{q}(z) q\left(\frac{m_{\Pi_t}^2}{sz}\right) \right] . \end{aligned} \quad (23)$$

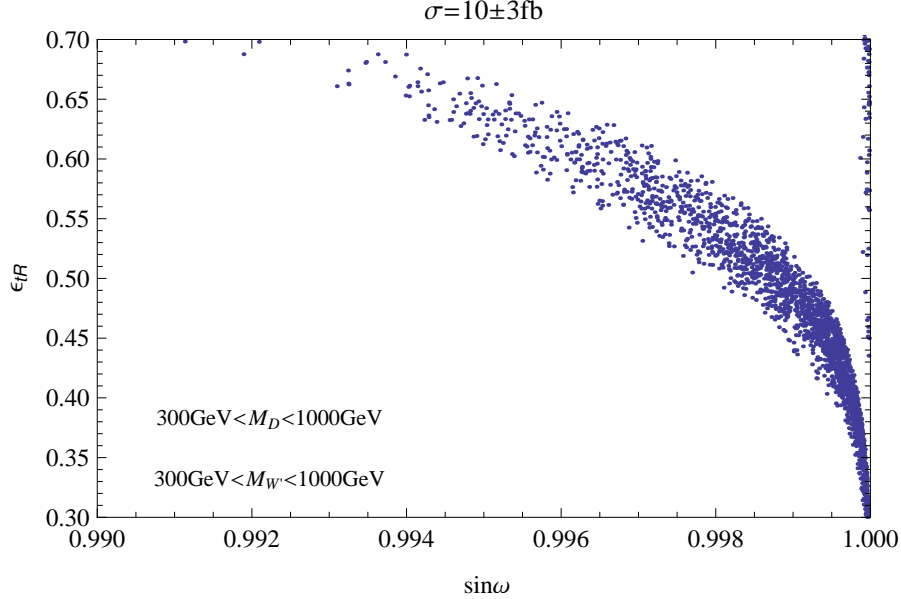


FIG. 1: The allowed parameter space of $\sin \omega$ versus ϵ_{tR} .

Now, we proceed to study whether the neutral top-pion Π_t^0 can serve as a candidate for the observed resonance at 750 GeV. First of all, we will find the parameter space for Π_t^0 to give a signal given by Eq. (21). There are totally four free parameters — $\sin \omega$, ϵ_{tR} , $M_{W'}$ and M_D — relevant for our study. The allowed parameter space of $\sin \omega$ and

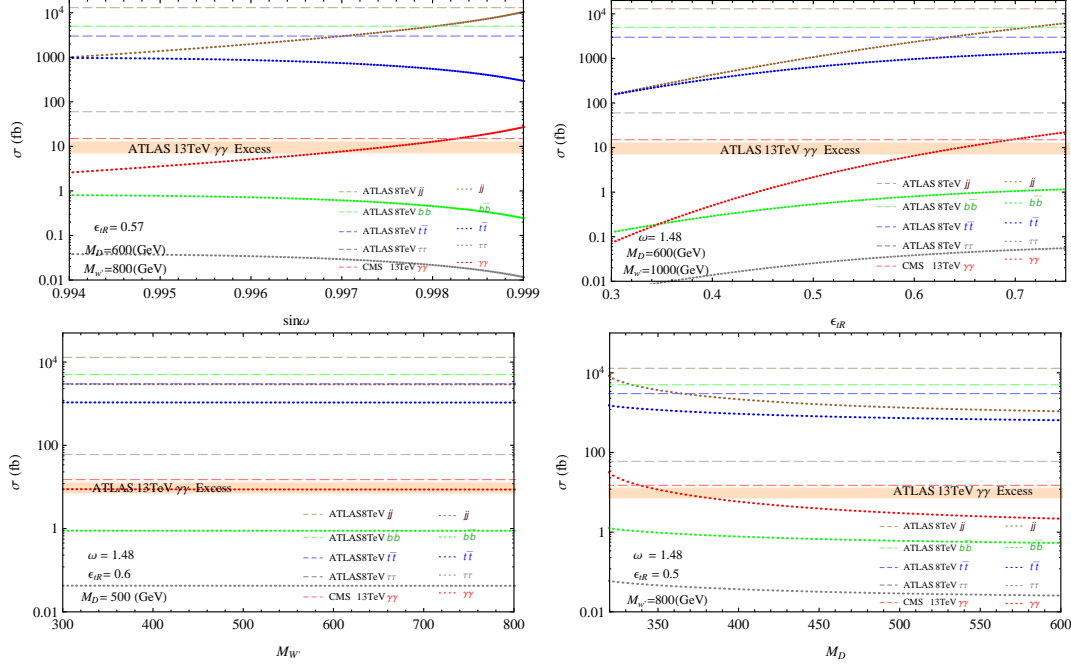


FIG. 2: The cross sections of $pp \rightarrow \Pi_t^0 \rightarrow jj, \gamma\gamma, t\bar{t}, b\bar{b}, \tau\tau$ (the jj here include gg and cc) at $\sqrt{s} = 13$ TeV against the four free parameters. The upper bounds for these cross sections extrapolated from the LHC results at $\sqrt{s} = 8$ TeV based on the approximation $\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}} \approx 5$ have also been shown.

ϵ_{tR} is shown in Fig. 1. In this calculation, we have imposed the constraint in Eq. (12) and allowed $M_{W'}$ and M_D to vary in the range $[300, 1000]$ GeV. As one can see from Fig. 1, $\sin\omega$ has to lie in a range extremely close to 1 while ϵ_{tR} ranges from 0.3 to 0.7. In Fig. 2 we have presented the cross sections of $pp \rightarrow \Pi_t^0 \rightarrow t\bar{t}, b\bar{b}, \tau\tau, gg, \gamma\gamma$ against one of the four parameters when the other three parameters are fixed to some particular values. It is apparent that these cross sections are more sensitive to $\sin\omega$ and ϵ_{tR} than the mass parameters $M_{W'}$ and M_D . In particular, the cross section for $pp \rightarrow \Pi_t^0 \rightarrow \gamma\gamma$ can be enhanced by increasing $\sin\omega$ and ϵ_{tR} . The upper limits for the cross section of each decay mode are also shown, which are extrapolated from the LHC searches at $\sqrt{s} = 8$ TeV [100–103]. One can see that the phenomenological consequences of a 750 GeV Π_t^0 are compatible with these constraints. Finally, we plot the possible total decay width of Π_t^0 as a function of $\sin\omega$ in Fig. 3. In most of the allowed parameter space, Γ is within 30 GeV, in agreement the observed one. But as $\sin\omega$ decreases from 1 Γ will grow rapidly, rendering the signal for $\sigma(gg \rightarrow \Pi_t^0 \rightarrow \gamma\gamma)$ unobservable.

Finally, let us briefly discuss the properties of Π_t^\pm and H_t . An interesting consequence of the TTM model is that it predicts Π_t^\pm to have the same mass as Π_t^0 (i.e., 750 GeV). On the other hand, the corresponding couplings for Π_t^\pm are given by

$$\frac{i\sqrt{2}\Pi_t^+}{v} (m_t \cot\omega \bar{t}_R b_L + m_b \cot\omega \bar{t}_L b_R + m_\tau \cot\omega \bar{\nu}_{\tau L} \tau_R + m_c \tan\omega \bar{c}_R s_L) + h.c. . \quad (24)$$

One immediately finds that the dominant decay channel of Π_t^+ will be $\Pi_t^+ \rightarrow t\bar{b}$ or $\Pi_t^+ \rightarrow c\bar{s}$, depending on the value of $\sin\omega$. Accordingly, Π_t^+ can mainly be produced

in association with a quark via the process $gb \rightarrow b \rightarrow t\bar{t}\Pi_t^+$ or $gs \rightarrow s \rightarrow c\bar{c}\Pi_t^+$, while the contributions from electroweak processes such as $u\bar{d} \rightarrow W^+ \rightarrow H_t\Pi_t^+$ are negligibly small. By comparing Fig. 10 and Fig. 13 of Ref. [85], we can see that the production cross section for Π_t^\pm is about one order of magnitude smaller than that for Π_t^0 . In combination with the fact that the dominant decay channels of Π_t^\pm are hadronic which tend to be masked by high backgrounds, this means that a direct search for Π_t^\pm is difficult at the present stage. Last but not least, we point out that H_t is a unique candidate for the 125 GeV resonance discovered in 2012 [109, 110] which is widely believed to be the (SM) Higgs boson. The reason lies in the fact that in the preferred parameter space region $\sin\omega \sim 1$ the electroweak symmetry breaking mainly originates from a non-vanishing VEV of the top-Higgs field Φ , leading H_t to behave in a similar way as the SM Higgs boson. The latter point can be easily seen from the coupling strengths between H_t and the SM particles. For instance, the coupling strength for $H_t W^+ W^-$ is approximately $g^2 v \sin\omega/2$ [84, 85] which can be reduced to that in the SM case by taking $\sin\omega = 1$. In addition, from Eq. (9) one can see that H_t has a mass suppressed by $\cos\omega$ (which takes a value ~ 0.1 in the viable parameter space region) as compared to $M_{\Pi_t} = 750$ GeV, in good qualitative agreement with the experimental results. Quantitatively, one always has the freedom of specifying a suitable value for the λ in Eq. (9) to obtain an 125 GeV H_t precisely.

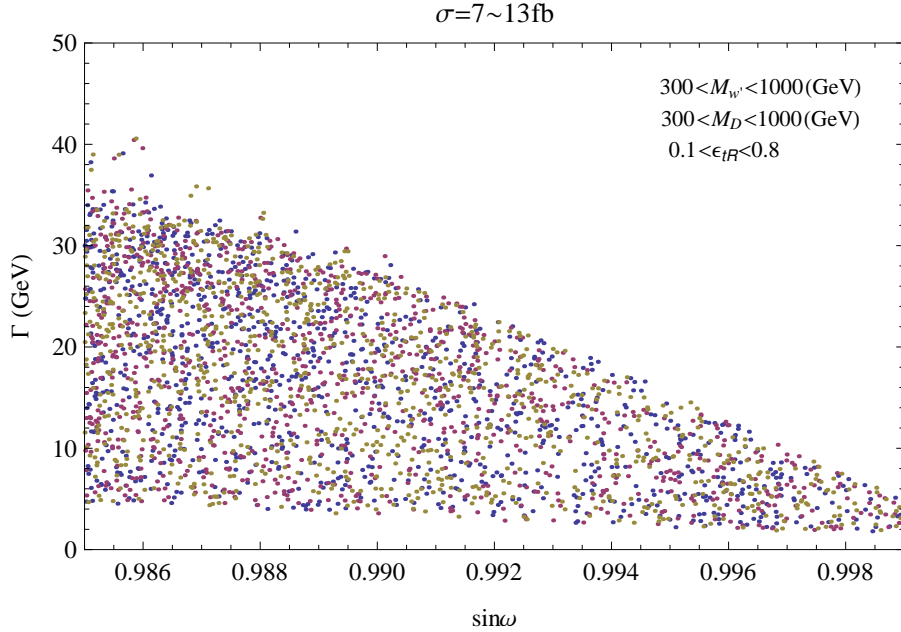


FIG. 3: The possible total width of Π_t^0 against $\sin\omega$.

III. SUMMARY

While the 750 GeV diphoton excess necessitates a further collection of data to be confirmed or ruled out, it is still worthwhile for us to explore various new physics that can naturally account for this signal and their physical implications. Motivated by the

possibility that this excess may be due to one composite (pseudo)scalar of a mass around 750 GeV, we investigate whether TC models can accommodate such a signal and find that a variety of TC models are unable to fit with the experimental result. These specific models include the original one-family model of FS [104], variant one family model [105], LR multiscale model [106], TC Straw Man model low scale [107], MR Isotriplet model [108] and top-color assisted TC models [83]. Most of these models have a too large width for $\Pi_t^0 \rightarrow t\bar{t}$ to give a satisfying result. Only in variant one family model can the total width of Π_t^0 may be lowered to ~ 45 GeV. But at this time the cross section is smaller than the observed signal by two order of magnitudes.

Most of our attention has been paid to the TTM model which is phenomenologically viable. It is found that the identification of Π_t^0 as the reported resonance has important implications: The parameter space (particularly that for $\sin\omega$) is strongly constrained, making the model more predictive. Hence we may confirm or rule out the possibility of Π_t^0 being the 750 GeV resonance by paying particular attention to this channel. Furthermore, the TTM model predicts two charged top-pions Π_t^\pm of the same mass as Π_t^0 . Unfortunately, they are difficult to discover owing to a combination of low production cross section and high backgrounds for their decay products [85]. Finally, it is interesting to note that H_t may serve as a unique candidate for the observed 125 GeV resonance. To summarize, the TTM model can explain the recently observed diphoton excess and has testable predictions, thereby deserving some attention.

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